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Recent Combat Aircraft Life Cycle Costing Developments within DERA

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ABSTRACT

In an effort to permit the procurement of more cost-effective military equipment, several studies have been performed in collaboration with two leading UK Universities. This paper describes the rationale and requirements of both University programmes, and gives details of the methods and some of the results generated. Rather than a broad overview of many different research activities within the Defence Evaluation and Research Agency (DERA), the purpose of this paper is to give as detailed a view as is possible of two recent studies, and the future developments that will stem from them.

The first part of the paper describes a tool developed for the design and optimisation of combat aircraft for minimum Life Cycle Cost (LCC), whilst the second part explains the evolution and optimisation of a long-range ground-attack aircraft designed for minimum support. The LCC model excludes 'deep overheads', restricting the use of the models to the comparison of similar weapons systems (combat aircraft) with a common set of design objectives and performance constraints. The support estimation methodology of the second part makes use of known aircraft design variables to predict reliability and maintainability of the aircraft. Both research activities, and the subsequent development at DERA, should have a positive effect on the aircraft design process.

INTRODUCTION

The Defence Evaluation and Research Agency (DERA), provides scientific advice, innovative engineering solutions, and a broad range of technical services to the UK Ministry of Defence (MoD). The Centre for Defence Analysis is a sector of DERA, and is primarily concerned with performing operational analysis to provide authoritative and impartial advice to decision-makers within MoD and across the Armed Forces. As part of a larger effort to reduce the cost of military equipment, particularly operation and support cost, a number of research studies were performed in collaboration with Cranfield University and Imperial College, on the conceptual design of combat aircraft for reduced support and LCC.

LCC is a complex subject that is concerned with quantifying options to ascertain the optimum choice of assets and asset configuration. When related to a combat aircraft, this leads to the type of aircraft, its specification, and configuration. In order to provide defensive and strike roles effectively in the face of improvements in the potential enemies' forces, it has been necessary to continually advance the performance, capability, survivability, and support characteristics of the aircraft, its associated weapon systems, and countermeasures. This has resulted in increasing complexity of aircraft and systems and, in most instances, increasing costs, in both absolute and real terms. Clearly, almost any new technology could influence the LCC of the aircraft system. For this reason this paper is not intended to be a comprehensive review of all the LCC research taking place within DERA, but rather an overview of two DERA-sponsored University research programmes, and their intended development.

The US Department of Defence first applied Life Cycle Costing to military projects in the early 1960's. It has become more popular and important in the procurement of military equipment, as the budgets for the World's fighting forces are ever-increasingly tightened. The reasons for this are numerous and highly involved, needless to say that the end of the Cold War, the global recession of the early nineteen-nineties, and the flood of low-initial-cost equipment from the former Soviet Union have all played contributing roles.

With waning public support for defence expenditure, policy makers must be seen to be cutting defence budgets in order to facilitate increases in spending on welfare and other domestic programs. Thus, military equipment must now be shown to present 'value for money' in both the long and the short term. 'Value' is difficult to quantify in the military sense, leading the current research activities to facilitate reductions in through-life costs of aircraft designed for a specified level of capability, mission performance, and operational requirement. In this way, 'value' can be said to be maximised, as a set level of performance is delivered for the lowest total cost.

In most previous studies of military aircraft, the objective function (i.e. the variable subject of the optimisation) was most often mass, either empty, mission, or gross mass. In the civil world, direct operating cost is frequently the figure of most interest to airlines, as it is the figure that allows the operator to decide flight charges, and ultimately calculate profit. In the military environment, 'profit' is not shown, although peacetime costs of operation are still just as important. It would therefore appear that there is a need for a greater understanding of the main contributors to the costs of military equipment, not only for the acquisition phases, but also in their operation and upkeep, and perhaps a re-think in the way that equipment is designed.

The following sections of the paper briefly describe two DERA-sponsored University research studies. The first is a tool for the conceptual design of combat aircraft for minimum LCC, and was performed by the author[1] whilst at Cranfield University. The second describes a minimum support long-range, ground attack aircraft, the Low Support Vehicle (LSV), and was performed by Whittle[2], at Imperial College. There are many similarities between the two pieces of work, but the Low Support Vehicle was optimised for minimum mass, as no discrete measure of support was determined.

The aircraft conceptual design tools used are based on classical design methods, recently adapted and updated, and validated with published data. The engine performance modules consist of detailed thermodynamic models, modified for the current usage. New engine sizing and mass estimation routines were developed for both models. The LCC model is primarily activity-based, and is an amalgamation of several different methods, each written for a different phase in the system life cycle. The LSV methodology makes use of two measures of Support - the calculated levels of Reliability and Maintainability (R&M) for the aircraft, and the number of support aircraft required for a range of offensive missions.

Paper presented at the RTO AVT Specialists' Meeting on "Design for Low Cost Operation and Support", held in Ottawa, Canada, 21-22 October 1999, and published in RTO MP-37.

PART I - CONCEPTUAL DESIGN OF COMBAT AIRCRAFT FOR MINIMUM LIFE CYCLE COST

AIRCRAFT SYNTHESIS MODEL - The aircraft synthesis and optimisation model is implemented via a large FORTRAN code. Figure 1 gives a schematic representation of the overall operation of the program. It can be seen that the optimiser has ultimate control, and is responsible for altering the aircraft design and engine sizing parameters such that all constraints are met, and a minimum value of the objective function is achieved. For sufficiently accurate LCC prediction, the synthesis model must have an appropriate level of fidelity, and include realistic feature modelling and constraints. This was a difficult balance to strike within the time constraints of the study, and the LCC modelling routines may in future be added to the more capable aircraft synthesis models developed elsewhere within DERA.

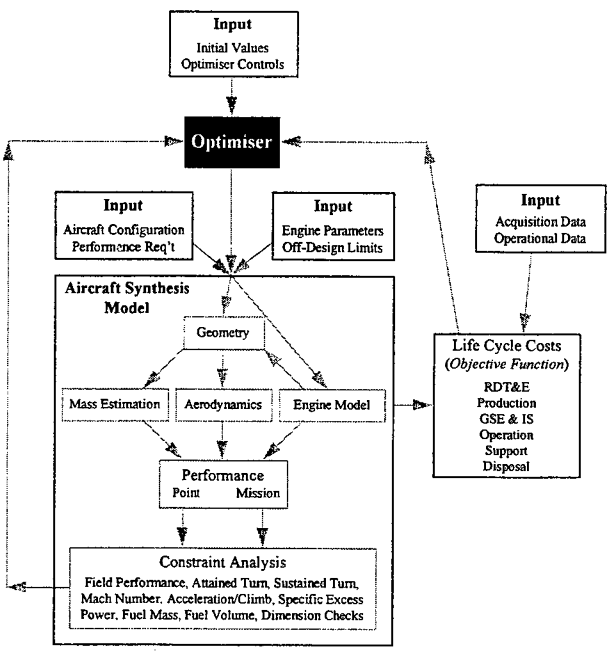


Figure 1. Overall Program Operation.

The first stage in the aircraft synthesis procedure is to read the relevant input data files and set the required parameters. The design options available include the aircraft type, configuration, number of crew, number of engines, etc. Further input data specifies the overall design requirements of the aircraft, including maximum level Mach number, diving Mach number, limit load factor, maximum payload, avionics mass, the number of weapon pylons, and other design drivers.

The parameter initialisation process also calls the engine design program. The engine thermodynamic cycle design is performed using data from the engine input file, which also contains off-design limits for the engine. This adds to the realism of the model by restricting the engine operating envelope. Once the cycle of the engine has been set it is not altered, and all subsequent engine calculations are performed to analyse the engine performance away from its design point. The above actions (i.e. file read and engine thermodynamic design) are only performed on the very first call to the synthesis. All of the following design procedures are performed every time the synthesis is called by the optimiser.

Component Sizing - Although the engine thermodynamic cycle has been specified, the physical size of the engine is yet to be defined. The main parameter used to determine engine size (in terms of both engine thrust and physical dimensions) is air mass flow rate, the value of which is determined by the optimiser. The engine off-design analysis program is called at sea level static conditions, and the values from this run, together with the original engine design data, are used to calculate the physical dimensions of the engine, using a bespoke method. The engine intake area and maximum nozzle area are generated for use in the aircraft geometry, mass, and drag prediction methodologies.

The remainder of the aircraft is then sized so that an overall configuration can be studied. The aircraft sizing process was kept deliberately simple, in order to keep the number of variables to a minimum, and improve robustness of the code. A large number of design variables can cause the optimiser to become trapped in local minima, and reduce the chances of true convergence. Figure 2 shows the overall sizing of the aircraft and the relevant major airframe design variables.

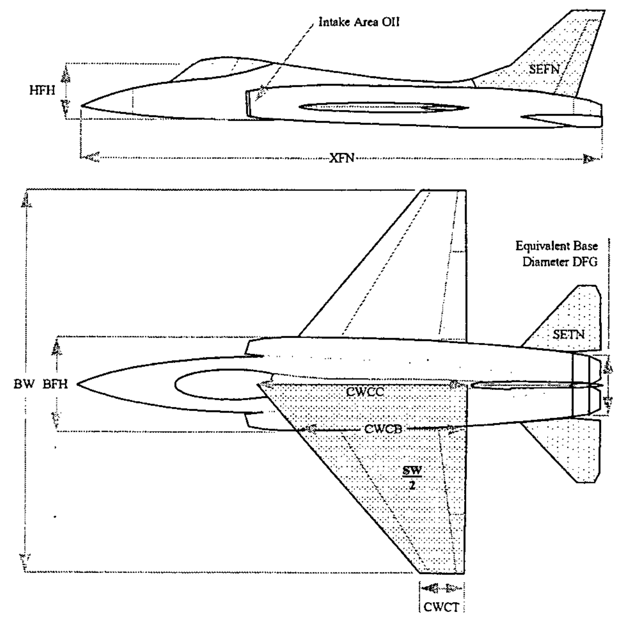


Figure 2. Aircraft Variable Definitions.

The size of the fuselage is determined using the maximum fuselage length, and the maximum effective fuselage diameter. From these two variables, and engine parameters calculated earlier, the remaining fuselage dimensions can be estimated. The width and height dimensions are driven by the maximum effective diameter, whether the aircraft has one or two engines, and the size of the engine(s). Both the height and width could have been varied separately, but a single variable was felt to be beneficial, as explained above. For both single and twin-engine aircraft, constraints are added to ensure that the fuselage cross-sectional area is large enough to accommodate the engine(s), and that the height is at least 20% larger than the maximum diameter of the engine.

The optimiser provides values for gross wing area, aspect ratio, taper ratio, leading-edge sweep, and thickness/chord ratio; all other wing variables, including tip and centreline chords, are found from standard geometry calculations. These values are used in the calculation of aerodynamic performance and wing fuel storage volume. The sizing of the empennage is performed using parametric sizing equations developed for this methodology, and the results are used in the aircraft mass and drag estimation procedures. For both the tail and fin, other parameters are also calculated, namely aspect ratio, thickness/chord ratio, and mean chord. All wing, fin, and tail parameters required by the synthesis have now been generated, concluding the geometric definition of the aircraft.

Mass Estimation and Volume Accounting - One of the most important processes in the design of any aircraft is the estimation of the aircraft mass, which in this methodology, is calculated from the sum of the individual component masses. However, many of the component masses are themselves a power function of the aircraft all-up mass, and the process becomes an iterative procedure to converge on the correct mass of the current design configuration.

The mass estimation method is implemented in such a way as to mimic the historical use of composite materials; the first structural component mass estimated is that for the empennage, followed by the wing, and finally the fuselage. Systems masses are found using semi-empirical methods, with separate parametric equations for each of the major systems. Fuel mass is calculated based on a fuel fraction value supplied by the optimiser. From the mass of structure, systems, and fuel, the aircraft gross mass and mission masses are calculated. Although the above methods are relatively simple, Figure 3 shows that surprisingly accurate results are achieved when the aircraft is treated as a whole system.

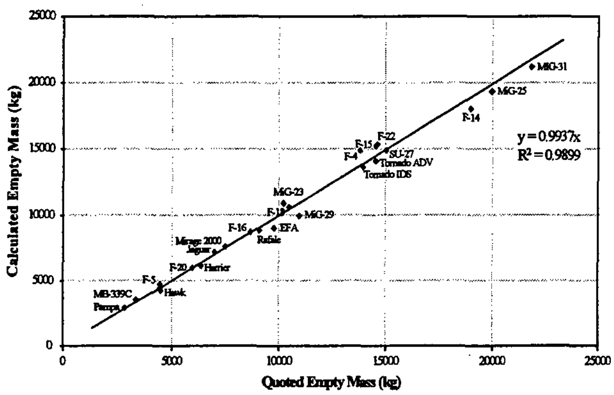


Figure 3. Mass Estimation Correlation.

The final process in this section of the code is to ensure that there is sufficient volume available for fuel carriage. Assumed system densities are used to subtract relevant volumes from the total available in the wings and the fuselage, and is implemented as an optimiser constraint.

Aerodynamic Modelling - The aerodynamics module consists of three models. The first predicts available lift coefficient based on wing configuration and geometry, Mach number, and the presence of high-lift devices. The second calculates the angle of attack from the lift-curve slope, which is based on the clean wing geometry and flight Mach number, and contains a simple correction for the effects of vortex lift. The third section is the largest and most complex of the three, and calculates the drag of the aircraft based on its geometry, lift coefficient, configuration, and the presence of external stores and retractable components. Due to the level of complexity of the models, and in the interests of brevity, the aerodynamic models are not expanded further in this paper.

Propulsion Modelling - Propulsion modelling is performed using two thermodynamic codes, ONX and OFFX, written by Mattingley[3]. The capability of the models has been limited, for the purposes of this study, to reheated turbojets and turbofans, and several improvements have been made from the original codes. Engine design starts with on-design analysis, which presumes that all design choices are still under control and that the size of the engine is yet to be fixed. The performance parameters are given as 'specific' values, normalised with engine size, and each complete set of design choices will result in an engine with its own operating and performance characteristics. ONX performs this section of the engine design, and from relatively simple starting values, the nature of the engine cycle is determined. The user can determine the design cycle of the engine simply by changing the parameters in the input file.

Once the engine cycle and limitations have been set, the engine is analysed away from the design point by the off-design analysis program, OFFX. This program returns all of the major performance parameters for a particular engine and flight condition. From these values, and calculating the installation losses, the thrust available and fuel burn can be estimated at any flight condition and throttle setting. An optimiser constraint has been added to ensure that the thrust available meets or exceeds the required thrust at all flight conditions. The constraint is very useful, as it allows the thrust at every mission phase to be checked using only a single variable. It ensures that the aircraft can complete supercruise and other high-thrust mission legs without the need for extra point performance constraints, for which the aircraft mass will not be known at the mission definition phase.

Once the engine air mass flow rate has been established for a particular application and the design choices and limitations have been set, the mass and physical dimensions of the powerplant are calculated. Continuing a theme suggested by Whittle[2], a new engine dimension and mass estimation methodology has been developed. The new models are based on the major engine design drivers; air mass flow rate, bypass ratio, compressor pressure ratio, number of shafts (although ONX & OFFX only deal with two-shaft engines), and reheat thrust increase. The results are very promising, but there is a question to be resolved over the accuracy of engine mass prediction in the 125-175kg/s air mass flow rate range.

Point and Mission Performance - Point performance calculations are used to compare the delivered performance of the designed aircraft with the required performance figures. They play a crucial role in the sizing of the aircraft, as the performance constraints determine the aircraft wing loading and thrust/weight ratio. The sizes of the wing and engine have a major impact on the overall design of the aircraft, and therefore the point performance calculations must be accurate, if a realistic design is to be produced. The synthesis is able to consider up to ten different point performance constraints; the amount of fuel, payload, engine operation (maximum or military thrust), and the individual point performance level can be specified. Of the ten available point performance constraints, the user has a choice of seven different constraint types. These include take-off and landing, attained turn rate, sustained turn rate (both in either g or °/s), specific excess power, maximum speed, and time-to-climb/acceleration. Maximum height can also be calculated, but is not included as a constraint.

The mission performance calculations work, for the most part, in a similar manner to the point performance constraint analysis methods, many of the algorithms being identical. The main difference in this section is that the major factor being calculated is the amount of fuel burned for each mission leg. The sum of all of these masses, plus a user-defined reserve factor, gives the total mission fuel mass, one of the single most important values in the sizing of the aircraft. Up to thirty mission legs can be specified from eight phase types, those being; engine run, take-off, climb/accelerate/descend, cruise, combat manoeuvres, weapons drop, loiter/CAP, and landing. Range credit is ignored for climb/accelerate/descend and loiter phases. Supercruise legs are specified by setting the cruise Mach number, and restricting the use of reheat.

LIFE CYCLE COST MODEL - The LCC module is based on several models that have been acquired and developed from many different sources, and has been split into the areas most often quoted in the available literature. Those are Research, Development, Test and Evaluation (RDT&E); Production; Ground Support Equipment and Initial Spares (GSE&IS); Operation and Support (O&S), and Disposal. Each life cycle phase model is represented by a subroutine, with all of the data coming either from the aircraft synthesis models, or the LCC input file. This file contains data such as procurement and operation data, production rates, fuel costs, as well as cost factors for security, flight test, and stealth considerations.

Research, Development, Test, and Evaluation - The RDT&E phase covers all areas of research and development prior to full-scale production of the first production aircraft. It includes; concept definition, design studies and integration, wind tunnel models and testing, laboratory testing, production of static and flight test airframes, avionics, software, propulsion development, flight testing, integrated logistics support, and program oversight. RDT&E typically makes up about 10-15% of the LCC of modern, low-production ($\approx$ 500) combat aircraft, but is obviously affected by the number of aircraft over which this cost can be amortised. The method for the calculation of airframe development costs is taken directly from a method developed by Burns[4].

The methodology breaks the development procedure into many different activities, with the effort for each being estimated, and then multiplied by an appropriate labour rate to calculate cost. It can thus be thought of as an 'Activity-Based Costing' (ABC) procedure. The airframe cost model is based on parametric estimating techniques, using airframe mass, and several user-specified or design-dependent factors to allow for differences in the designs. The method used for engine development cost estimation is taken from a model developed by Birkler[5]. It uses thrust, Mach number, and turbine inlet temperature as the main cost drivers, and has been found to be accurate for the limited data available. Avionics and software development costs have proven problematic; avionics cost is based on uninstalled mass, whilst software cost estimation uses the number of lines of code and a number of user-defined complexity factors.

Production - This includes production engineering design, production investment (manufacturing facilities, tooling, jigs and fixtures), manufacturing labour, quality control, material and equipment, profit, overheads, administration, and purchasing of engines and avionics systems. These costs, divided by the number of aircraft make up the Recurring Flyaway Cost. Figure 4 shows a comparison of quoted and calculated recurring flyaway costs.

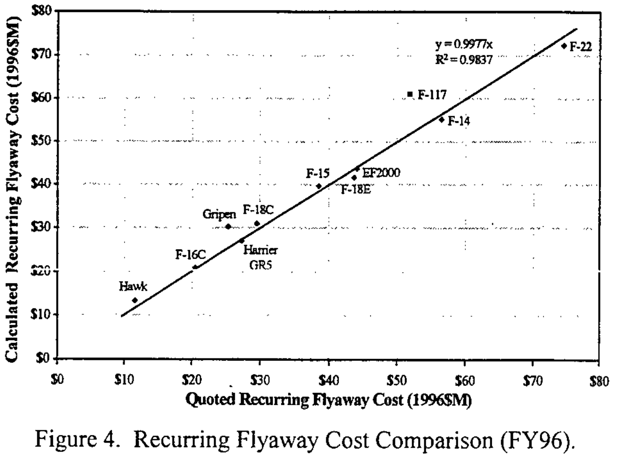


Figure 4. Recurring Flyaway Cost Comparison (FY96).

Production costs typically account for 30-35% of the total LCC of modern combat aircraft; the cost per aircraft decreases with number of aircraft built, as 'learning curve' theory and economies of scale are applied. The airframe production cost models are taken from the activity-based cost model derived by Burns, whilst the engine cost model is taken from a USAF Flight Dynamics Laboratory report[6]. Avionics cost models are based on uninstalled avionics mass. The total of the two major costs above (RDT&E & Production), divided by the total number of aircraft built, is called the Unit Acquisition Cost.

Ground Support Equipment and Initial Spares - This area of LCC is very difficult to estimate because of the equipment requirements for a particular weapon system. In keeping with suggestions made by several members of the costing community, GSE&IS cost is simply a fraction of the aircraft recurring flyaway cost, resulting in about 5% of total LCC.

Operation and Support - Operation and support (O&S) costs for modern combat aircraft can be split into several parts, all of which will be contributors to the cost of using combat aircraft in a peacetime operating regime. In wartime, the cost of operation and support becomes much less important, with all resources made available to win the particular conflict. O&S costs comprise: operation personnel; support personnel; service allowances, personnel support, and training; unit level consumption; contract costs for airframe, avionics, propulsion, and supply; sustaining support funds; and basing overheads and upkeep. The breakdown of O&S costs used follows the methods and structure suggested by the US Office of the Secretary of Defence in their 'Operating and Support Cost Estimating Guide'[7]. The O&S cost is calculated for one Main Operating Base, as this will have a significant effect on the staff requirements for the particular aircraft. This gives the added benefit that the model allows different basing concepts to be investigated, whereas many previous cost models considered the total number of aircraft procured.

One of the largest single O&S costs is that for mission personnel, the vast majority of whom are involved with First and Second Line maintenance. In order to calculate the number of maintenance personnel, the method first estimates the total maintenance effort required by the aircraft, using a parametric method. The number of First and Second Line operation personnel is calculated from the number of aircraft, crew ratio, the annual flying time per aircraft, and the total maintenance effort per flying hour. Support personnel numbers are calculated from the number of operations personnel and the number of aircraft. A separate section of the O&S model estimates the costs of Officer and Enlisted personnel training costs, training funds, and permanent change of station allowances. The models were adapted and updated from a US Navy report[8], and the values were calibrated against RAF Cost Of Support Spreadsheet data.

Unit Level Consumption attempts to capture the costs for all consumables used in operating the aircraft, including fuel, oil, lubricants, maintenance materials, miscellaneous support supply, depot level reparables, and temporary additional duty. Contract costs for the aircraft comprise what was thought of as Third and Fourth Line maintenance. With the potential re-structuring of the RAF, it was advised that it might be more applicable to treat these values as annual contract costs. The costs can be split among the three main aircraft systems - airframe, propulsion, and avionics - and supply. All of the contract cost models need updating, and work is currently underway to improve accuracy and increase the number of cost drivers. Supply contract costs capture the cost of

shipping airframe, engine, and avionics components between the base and the contractor, and some of the costs for the supply of unit level consumption materials. The final two O&S cost models deal with Sustaining Support, and Installation Support Funds. Sustaining support includes the cost of replacement support equipment, modification kit procurement, and sustaining engineering support. Installation support costs are made up of personnel pay and allowances, material, and utilities needed for the maintenance of the base.

The sum of all of the previously calculated values gives the total O&S cost for one year in 'then-year' dollars, which is then multiplied by the number of years in service, and can be 'discounted' using standard techniques. The model does not currently contain timescale estimates for development and production, making the discounting process slightly inaccurate, as a lack of discounting applied to the acquisition phase will result in those costs appearing to be larger than they really are. The discounted O&S costs for a life of thirty years at a rate of 6% per annum is found to be only 13.765 times the first annual cost, as opposed to the 30 times that would be applied if discounting were ignored. The cost calculated by the LCC model, for the individual aircraft, contains the total then-year O&S cost divided by the number of aircraft on the base. The O&S phase typically contributes about 50% of the LCC for modern combat aircraft, and it is in this area that the largest LCC savings can be made. Reduction in O&S costs can be achieved by reducing one of many contributing factors, e.g. maintenance effort, fuel burned, aircrew numbers, etc.

Disposal - This could amount to a wholly negative cost if the aircraft were sold intact at the end of its useful life. As this is very unlikely, the disposal cost model consists of the following contributors; disassembly labour, disposal of non-reusable material, sale of scrap material, and resale value of on-board equipment. Depending on the relative values of these different components, the total disposal figure could be positive (i.e. a cost), or negative (a credit). The resale of systems, such as the engines and avionics, is thought to be unlikely, as technology in these areas changes so quickly that, for the moment, the value of these items has been neglected.

Total Life Cycle Cost per aircraft is simply the sum of the different cost phases already calculated, apportioned to different numbers of aircraft, depending on the Life Cycle phase. Figure 5 gives an example then-year LCC breakdown for a modern combat aircraft, having a large composite materials content, which has the effect of increasing disposal costs. Encouragingly, O&S costs now appear to make up a smaller fraction of the total LCC compared with the last generation of combat aircraft, where operation and support costs typically contributed 60-70% of total LCC.

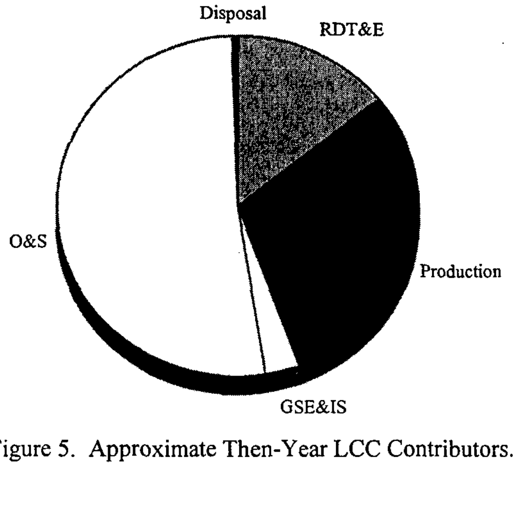


Figure 5. Approximate Then-Year LCC Contributors.

EXAMPLE RESULTS - In order to demonstrate the model capabilities, a number of aircraft solutions to a single mission specification were generated, optimised for minimum LCC. Aft-tail, delta, and delta-canard designs were produced with single and twin engines, and with options for crew and fin numbers. A notional air-intercept and combat mission was used, shown in Figure 6, together with rigorous point performance parameters, to produce a range of conventional semi-stealthy high-performance combat aircraft.

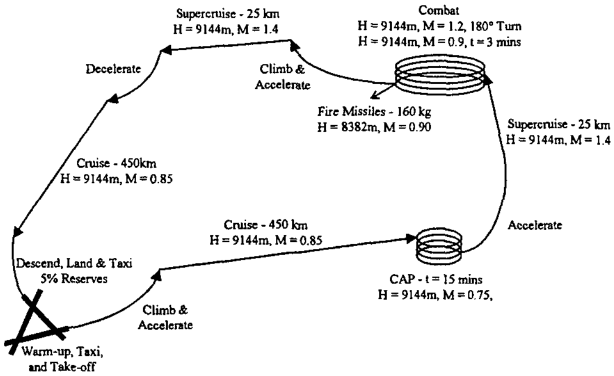


Figure 6. Aircraft Mission Performance Requirements.

Ground roll was limited to 250m for take-off and 500m for landing with full mission payload (475kg) of external weapons, and 95% fuel. Two attained turns were set; 7g at 12750m, M = 1.4, and 7.5g at 10805m, M = 0.9. Two sustained turns with reheat were specified; 5g at 6050m, M = 0.8, and 3g at 12825m, M = 1.6. All turn constraints were said to have full mission weapons load and 50% fuel remaining. Excess thrust values were checked at 11500m, M = 2, and sea level, M = 1.2, with full weapons load, and 50% and 80% fuel respectively. The final point performance constraint was for a time to climb. Initially, the aircraft was at sea level and M = 0.25, climbing to 9144m and M = 1.5 in 90 seconds; mission weapons mass and 50% fuel were assumed at the start.

The aircraft is assumed to be built by a collaborative group of two major and two minor partners, with a total buy of 620 aircraft and a production rate of 4.5 per month. FY2000 was assumed as the accounting year. The aircraft is to be operated from dispersed main operating bases of three squadrons (39 aircraft) per base, with a three-tier maintenance strategy - First and Second Line on the base, as well as Third Line contracts. It is to have a life of 25 years, at 240 flight hours per year, giving a total flying life of 6000 hours. 'Deep overheads', such as the cost of fighter control, are ignored, as are other costs not affected by the design of the aircraft.

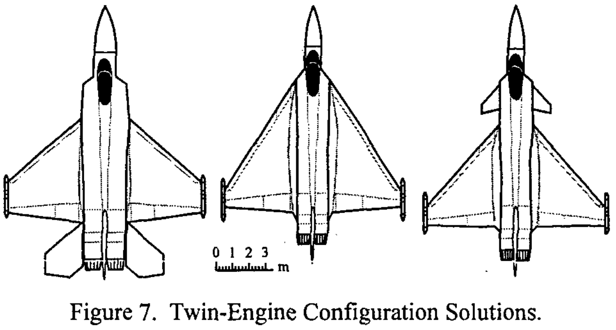
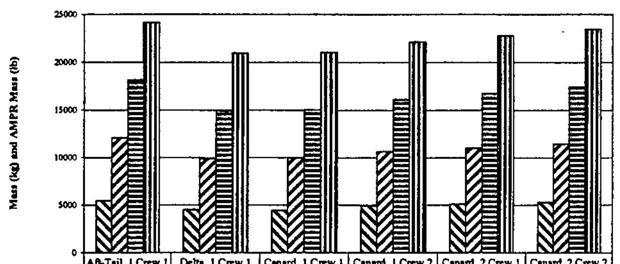


Figure 7. Twin-Engine Configuration Solutions.

Visualisations of the resulting one-crew, twin-engine, single-fin, configurations are shown in Figure 7. As can be seen, the delta and delta-canard designs are smaller than the equivalent aft-tail aircraft, although the delta will have lower agility than

the other two. The aft-tail aircraft can probably be the most 'stealthy' with the least compromise from near-optimum placement of control surfaces, which would most significantly affect the delta-canard. Thus, all of the proposed solutions are viable designs having particular strengths and weaknesses.

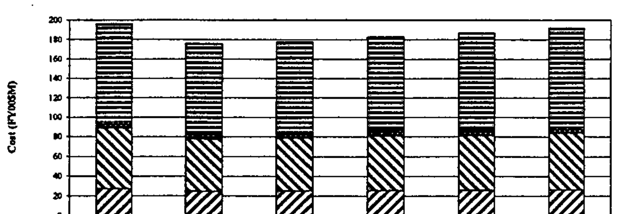
Fuel, empty, mission, and gross masses are shown in Figure 8, where mission mass is the mass of the aircraft, including crew, fuel, and weapons payload. The mass figures confirm the relative sizes of the aircraft, with the delta and canard-delta aircraft seen to be the lightest.



	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Fuel Mass	5475	4509	4457	4921	5095	5304
Empty Mass	12113	9880	10001	10632	11003	11470
Mission Mass	18162	14964	15033	16127	16773	17449
Gross Mass	24187	20989	21058	22152	22798	23474

Figure 8. Twin-Engine Mass Breakdown.

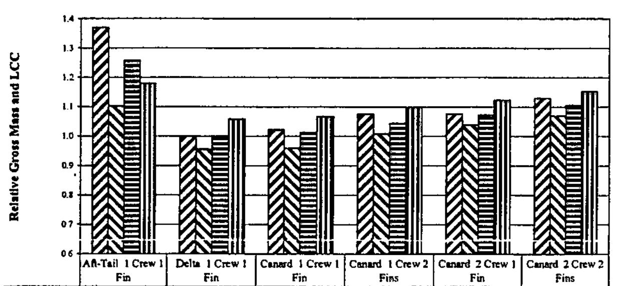
The costs for the various configuration options are shown in Figure 9. As expected for aircraft of similar technology levels, the costs change roughly in proportion to the mass, with all proportionate mass increases being greater than the relevant cost increases, except for the delta-canard design. This is due to a change in the driving performance constraints between the delta and canard-delta solutions, resulting in only a very small mass increase, but a larger cost increase, due to the increased complexity of the canard-delta aircraft.



	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Total	196.188	176.063	177.682	182.975	186.927	191.830
Disposal	0.973	0.776	0.798	0.838	0.831	0.884
O&S	99.948	92.247	92.662	95.122	99.058	100.812
GSE&IS	6.243	5.352	5.436	5.643	5.646	5.872
Production	61.542	52.756	53.587	55.627	55.657	57.876
RDT&E	27.481	24.932	25.199	25.744	25.736	26.385

Figure 9. Twin-Engine LCC Breakdown.

A comparison of the relative mass and cost increments relative to the single-engine delta (the lightest and cheapest aircraft) is presented in Figure 10.

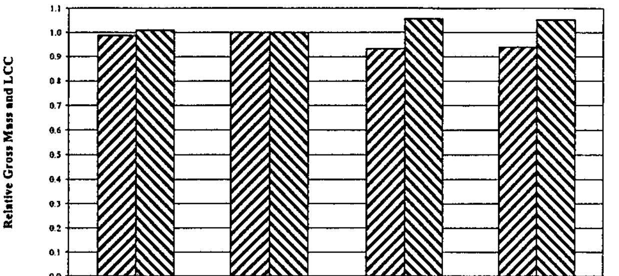


	Aft-Tail 1 Crew 1 Fin	Delta 1 Crew 1 Fin	Canard 1 Crew 1 Fin	Canard 1 Crew 2 Fins	Canard 2 Crew 1 Fin	Canard 2 Crew 2 Fins
Mass - Single	1.371	1.000	1.022	1.076	1.076	1.130
Mass - Twin	1.102	0.956	0.959	1.009	1.038	1.069
LCC - Single	1.257	1.000	1.014	1.044	1.073	1.106
LCC - Twin	1.179	1.058	1.067	1.099	1.123	1.152

Figure 10. Relative Mass and LCC – Single vs. Twin Engine.

It can be seen that for every equivalent aircraft configuration (except the single engine aft-tail aircraft, which is not a fully converged solution), the mass of the twin engine aircraft is lower, but the LCC has increased. This result is interesting for two reasons. Firstly, it questions a commonly held perception that, for a given set of requirements, a single-engine aircraft will be smaller and lighter than a twin-engine configuration. Secondly, it shows that for significant configuration changes cost is not proportional to mass.

This second observation prompted further research in to the differences between aircraft optimised for mass and LCC. For both single and twin-engine canard configurations (which had previously been judged to offer a good balance of cost and combat effectiveness), solutions were produced with gross mass as the optimiser objective function. The results of the comparison appear in Figure 11, where the relevant objective function is minimised in all cases.



	Single Engine Mass-Optimised	Single Engine LCC-Optimised	Twin Engine Mass-Optimised	Twin Engine LCC-Optimised
Gross Mass	0.987	1.000	0.933	0.939
Total LCC	1.009	1.000	1.057	1.053

Figure 11. Relative Mass & LCC – Mass vs. LCC-Optimised.

Although the differences are small when presented as above, the total savings for an aircraft programme, with no loss of capability, are significant. The savings above correspond to a monetary value of FY00$M970 for the single-engine aircraft, and to FY00$M435 for the twin-engine solution. These savings increase once discounting is included, due to the reduced influence of the slightly increased O&S costs. In future, the difference between aircraft optimised for mass and cost will increase as the R&M and LCC models are improved to reduce their dependency on mass.

Other studies have also been performed to investigate the effects of internal weapons carriage, composite materials usage, and more electric aircraft (MEA) technologies on aircraft mass, performance, and cost. The LCC model requires further development, particularly for the R&M model, and the manpower scaling from it. This will improve accuracy and confidence in the models, and should produce greater differences in aircraft optimised for mass and LCC. Long-term, this will allow greater savings in through-life cost, as aircraft become closer to true minimum-cost designs. What the objective function should be, and the confidence that is placed in it are subject to discussion; increased modelling and understanding of the real cost drivers can only be of benefit.

<u>Future developments</u> – New versions of the cost model are intended to be included with the more detailed design and optimisation tool used by DERA's Air Vehicle Performance group. This model offers higher aircraft modelling fidelity, improved propulsion calculations, and has been validated more thoroughly than the current aircraft synthesis model. The combination of the improved LCC model, higher fidelity aircraft models, and up-rated optimisation software should dramatically increase DERA's capability to 'Design for LCC'. This should enable significant improvements in the cost-effectiveness of future British/European combat aircraft.

PART II - THE LOW SUPPORT VEHICLE

OVERVIEW - A fresh approach to solving the problem of affordability of future combat aircraft was proposed[9], involving the formulation of a Low Support Vehicle (LSV) concept, specifically directed at minimising through-life operating and support requirements. The outline specification for the concept design of the LSV, and a description of the principal characteristics of the LSV, was established[10], so that a single detailed concept formulation could be produced. The Department of Aeronautics, Imperial College, London undertook the study, under a three-year contract. The purpose of the study project was to demonstrate the effects of aiming for drastic reductions in support costs for all parts of a combat aircraft design, so allowing a better trade-off to be made between support characteristics and other features.

This section of the paper summarises the evolution of the LSV design and indicates some of the supportability features incorporated. The method developed for the prediction of the reliability and maintainability (R&M) of the LSV is described, together with the outcome of the predictions. A separate assessment of the cost-effectiveness, design attributes, and supportability features of the LSV has been conducted, but is outside the scope of this paper.

Supportability - For the purpose of the study, a supportable aircraft was defined as one with low support requirements; a minimum expenditure of equipment, effort, and, ultimately, money is required for the aircraft to fulfil its assigned role. Supportability of the aircraft alone was considered as a fundamental consequence of R&M. This was derived from the assumption that everything that affects the direct support of a system, other than consumables, can be linked to the inherent R&M characteristics of the system. For the study therefore, supportability is the quality possessed by a supportable aircraft.

The usual perception of supportability is that it is simply the consequence of the R&M characteristics of the aircraft under consideration. However, this view can be broadened to encompass the supporting systems required by the aircraft to complete its mission. This brings in such systems as in-flight refuelling tanker aircraft, or escorting fighter aircraft. This idea of total system support requirement reflects the aircraft's capability as well as its R&M characteristics, and is dependent upon the aircraft's mission.

It was considered that a total system support approach would be used to evaluate the supportability of the LSV in comparison with other combat aircraft. A framework for the method of comparison was developed during the study, which could be completed with the application of the appropriate analysis tools. The concept formulation for the LSV took into account the direct influence of R&M. It also considered the impact on the total system supportability in terms such as the ability to operate from short or damaged runways, the need for air-to-air refuelling, and the deployability of the aircraft by provision of systems that would reduce the need for an extensive logistics tail.

Evolution of the LSV design - The LSV was intended as an exploration of the effects of designing to minimise the aircraft support requirement. The specifications[10] called for the design to be formulated for the offensive role, with key performance specifications being equivalent to the Tornado GR4. Deviations from the performance requirements were only to be made to reduce the support requirement without significant reduction in capability. The essential features of the Tornado GR4 adopted for the LSV are shown below:

Mission:	hi-lo-lo-hi penetration
Payload weight with max. fuel:	4000 kg
Max. low-level speed with stores:	Mach 0.92
Maximum load factor:	7.5g

The LSV was initially specified to have a hi-hi mission radius of 1400nm, compared to the published Tornado combat radius (un-refuelled) of 750nm, although this was subsequently modified to a more representative hi-lo-lo-hi profile of 1130nm. Take off and landing distance of 1565m was specified on the grounds that a supportable and deployable concept such as the LSV should be capable of operating from many different bases - published data shows 36 British civil airfields with runways of adequate length for this performance. Such performance is comparable to that of modern mid-sized civil aircraft such as the Boeing 757 and Airbus A319, indicating that a similar distribution of suitable airfields should be found elsewhere in the world. Although an unclassified study, the LSV project took into account open literature information on low observables and considered them as part of the design.

DESIGN PROCESS - It was appreciated that the LSV would be a novel configuration in many respects, so that it was not appropriate to design just a single aircraft using existing methods; several different solutions might be possible for some areas of the design. However, without actually reaching the final design process for the aircraft it was not possible to identify which features should be included, and where new methods would be required. To resolve these problems, a scheme was established for developing several configurations leading to the ultimate design. New methods were developed in parallel with the development of the configurations, so that the final configuration would incorporate not only the best design features, but also the most refined calculations.

The design philosophy of the LSV was intended to maximise supportability, but the approach leads to some significant impact on the overall design. Inherent component reliability, although obviously desirable, cannot ensure reliability of a complex system due to the large number of individual components. Improving the operating environment for sub-systems and even systems can significantly improve the reliability of an aircraft, but such improvements can only be achieved if they are considered early in the design process. For example, providing a better environmental control system and planning the layout of all systems to provide a favourable operating environment can only be done by giving supportability a high priority early in the design process. Similarly, de-rating systems, particularly the engines, may provide a more benign environment, thus improving reliability. However, to achieve the same performance targets, de-rated engines must be larger than those operating at their maximum rating, affecting much of the design.

The LSV philosophy also stresses simplicity and integration as means to improve reliability. The use of integrated avionics systems, capable of re-configuring to take over functions of failed units is one example, but the concept of integration and simplicity can be applied to a much more basic level. For example, the weapons bay door on the LSV combines many functions, facilitating the release of internally carried weapons, and providing access to refuelling points and other internal systems. The complexity of the weapon bay doors is not increased, but the increased functionality eliminates the need for extra doors for refuelling and maintenance. Accessibility of systems for maintenance is emphasised in the

early design phases; an inadequate initial basic configuration and layout of systems can never be recovered in the detailed design phase. Finally, the LSV design philosophy avoided reliance on the use of unproven or speculative technologies, the failure of which to realise their potential would fundamentally undermine the ability to achieve the LSV aim.

From the target specifications, a baseline configuration was formulated. The designations LSV A and LSV B were used during the baseline formulation so that the first configuration to be designed was called the LSV C. The LSV C is a single seat, flying wing aircraft with wing-tip fins and a short nose. It is predominantly constructed of composite materials. Internal weapons bays flank the single non-afterburning, de-rated engine. The LSV C was developed from the baseline configuration, and has a 50° leading edge sweep with leading-edge root extensions. The trailing edge is kinked, and supports four control surfaces - a pair of rudders and a pair of elevons. The aircraft is slightly statically unstable.

As a result of the experience gained during the design of the LSV C, in both configuration and methodology, two further LSV configurations, the LSV D and the LSV E, were produced. The LSV D is a low aspect ratio delta wing design with no horizontal or vertical tail and no protruding nose. A single chin engine intake leads to the single non-afterburning turbofan engine. The LSV E has a planform similar to that of the LSV C, but without the wing tip fins, being a flying wing with no protruding nose. The trailing edge has a pronounced kink around 40% of the semi-span. Two engine inlets are positioned on the upper surface of the wing, each feeding a non-afterburning turbofan engine.

Analysis of the LSV-D and LSV-E showed that both met their targets, and could be developed into extremely supportable aircraft. The LSV-E was considered a more operationally flexible design, so this configuration was chosen for optimisation, to produce the final LSV configuration, the LSV-F. The computerised methods used to design the LSV C, LSV-D and LSV-E were combined in an automated design synthesis very similar to the one described in Part I of this paper. Many of the aircraft design models, particularly mass and aerodynamic estimation methodologies, had to be updated to allow for the unconventional design, although the thermodynamic engine models were derived from the same source. Figure 12 shows the optimiser evolution of the configuration, with drawings of the aircraft at the start, after 14 and 28 iterations, and at the end of 42 iterations.

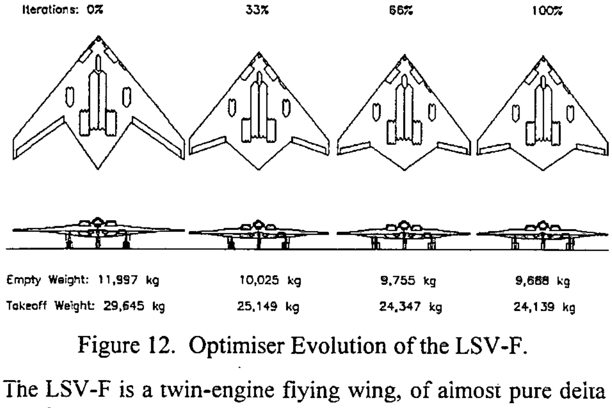


Figure 12. Optimiser Evolution of the LSV-F.

The LSV-F is a twin-engine flying wing, of almost pure delta planform, with a trailing edge kink at just under 50% semi-span. Two split elevons are the only control surfaces, and the aircraft is slightly unstable in pitch. It has a single centreline weapons bay with two doors, as well as the provision to carry external stores. The LSV-F configuration is illustrated in Figure 13, and by a computer generated image in Figure 14.

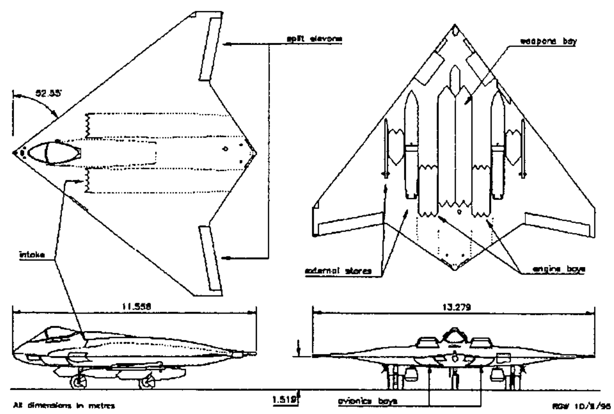


Figure 13. Final LSV-F Configuration.

Figure 14. LSV-F in Flight.

LSV-F SUPPORTABILITY - The LSV concept design is driven by the need to reduce support requirements. Aircraft supportability is achieved mainly by simplification, systems integration, redundancy, and by commonality of parts. The need for supporting systems is reduced by making the aircraft capable of autonomous operation; long range without refuelling, low-observable features, comprehensive electronic counter-measures, high speed at low level, and self-defence weapons all contribute to this. For maintenance purposes, all important systems can be accessed from the ground, without downloading weapons, via either the avionics bay, the cockpit, the undercarriage bays, or the weapons bay. On-board oxygen and inert gas generators (OBOGS/OBIGGS) and a multi-function integrated power unit reduce the need for ground support equipment.

The LSV-F structure employs composite materials to reduce fatigue, corrosion, and weight. A modular structure is used, possibly incorporating a damage sensing system, to allow on-condition maintenance and to reduce peacetime operating costs, through reduction of third and fourth line maintenance and no-fault-found (NFF) reporting. Many structural components are common, and there are no leading and trailing edge high-lift devices. The engines are de-rated, and do not have reheat capability. Engine installation and removal is achieved by means of a special trolley, and all maintenance actions can be effected from below, so avoiding damage to the upper wing skin. Due to the position of the intakes, there is little danger of foreign object damage (FOD) to the engines.

The main undercarriage is very simple and robust, the units being interchangeable between the left and right sides of the aircraft. Oversized tyres operating at low pressure give increased tyre life, and two wheels per main undercarriage strut reduce the kinetic energy per wheel, allowing simpler brakes. The nosewheel uses the same type of tyre as the

mainwheels, and the oleo shock absorbers are identical for the main and nose undercarriage. A titanium matrix composite could be used for the undercarriage, eliminating the need for corrosion inspection.

Whole fuel tanks are formed from composite material, to reduce leakage at tank joins. The tanks are foam-filled, and can be pressurised from the inert gas generating system. The weapons bay provides a benign environment, improving the reliability of weapons that may be carried on a number of missions without being expended. The gun is positioned to prevent interference with other aircraft systems and minimise the effects of vibrations from gun firing and ingestion of gun gas by the engines. A disposable cover is fitted over the gun port, and ammunition replenishment is carried out via the starboard main undercarriage bay. The avionics bays are easily accessible, and the windshield may be opened to access cockpit avionics. All sensors are readily accessible from ground level. Avionics reliability is enhanced by a closed loop environmental control system for the avionics bays.

The hydraulic system is of simple configuration, employing electro-hydrostatic actuators. The ultimate goal is to eliminate hydraulics to further reduce support costs. The on-board multifunction power unit provides engine start, emergency power, and auxiliary ground power. The power unit replaces ground support equipment, as does the on-board inert gas generator. The main utility locations are positioned to prevent any compromise to system accessibility if more than one maintenance task is being carried out simultaneously. Except for the cockpit (which has its own access ladder) and upper wing surface, all points can be reached from the ground without ladders or stands.

The supportability measures identified for the LSV-F are summarised in Table 1.

Structure	simple modular construction composite fatigue-resistant-airframe only four multifunction control surfaces self-testing structure
Propulsion	non-afterburning, de-rated engines full-length engine access doors simple engine removal concept fixed geometry air intakes reduced likelihood of FOD to engine
Alighting	interchangeable undercarriage components single tyre and oleo types for all wheels corrosion-resistant undercarriage low pressure tyres simple brakes
Systems	integrated avionics and sensors low number of hydraulic system functions replacement of secondary hydraulic actuators with electrical systems multi-function integrated power unit on-board oxygen generating system on-board inert gas generating system
Maintenance	very simple configuration access-driven design accessible avionics bays, >50% growth space easy radar access
Operational	capable of operation from civil airfields stealth and advanced electronic counter-measures allow operation with minimum support single crew in-flight refuelling if required integrated weapons loading/launching arm internal weapons carriage self-defence capability long range with internal fuel

Table 1. Supportability features of LSV-F.

RELIABILITY AND MAINTAINABILITY - Two quantitative measures of aircraft reliability and maintainability are generally available. These are the defect rate (DR), usually expressed as defect occurrences per 1000 flying hours, and the defect man-hour rate (DMHR), which is the number of man-hours spent rectifying the defects, again expressed per 1000 flying hours. The term 'defect', in the context of this study, refers to a failure or a fault, requiring corrective maintenance action (referred to as 'rectifying' the fault).

The defect rate is a measure of reliability; more reliable aircraft will have a lower DR. The DMHR is often described as a measure of maintainability. However, the DMHR cannot be taken as an independent measure of maintainability, since the man-hours spent rectifying the defects in a given number of flying hours will depend not only on how easy it is to repair the system, but how many times it needs to be repaired. An independent measure of maintainability is found by dividing the DMHR by the DR, to give the mean time to repair each defect (MTTR), in man-hours per defect. If the reliability (DR) and maintainability (MTTR) are known, the unscheduled overall maintenance requirement (OMR) can be found.

The approach of separating reliability and maintainability measures and then multiplying to find the overall maintenance requirement, rather than attempting to predict the DMHR directly, was considered to lead to a more accurate and robust prediction method. The two aspects of the OMR are driven by different factors. Reliability is dependent on factors such as complexity, loading, and component reliability, whereas independent features such as accessibility and test methods determine maintainability. The three measures of merit (DR, DMHR, and MTTR) were used as part of the overall LSV supportability assessment method, the most important part of which was the prediction of the LSV R&M.

Different R&M analysis and prediction methods are appropriate for different stages of an aircraft design process. Several existing reliability and maintainability prediction methods were examined during the study to determine their applicability to the LSV design process. It was concluded that insufficient data was available to use detailed design methods for the supportability analysis of the LSV. Further, existing methods for conceptual design analysis were too old and too simplistic. It was therefore necessary to develop a new method for the prediction of the LSV reliability and maintainability for use in the supportability assessment.

R&M Prediction - For the purposes of the study, aircraft were considered to consist of twelve systems: air conditioning; flying/operational controls; fuel system; hydraulic power and pneumatics; alighting/arrestor gear; oxygen; miscellaneous utilities; structure system; propulsion systems; armament systems/tactical avionics; navigation and communications systems; electrical and instrument systems.

The R&M prediction method used consists of a set of statistically derived equations, based on work by Harmon[11], and updated by Serghides[12]. The equations predict, separately, the reliability and maintainability of aircraft systems, which can then be combined to give total aircraft figures and an overall figure for the support requirement in man-hours per flying hour. Data for ten aircraft in current or past RAF service, plus two US-operated aircraft (used to derive only the reliability equations) were collated, mainly from official sources. All aircraft are jet-powered combat aircraft from advanced trainers through interceptors and strike aircraft to a long-range strategic bomber, although the results should be treated with caution for such a large aircraft.

The purpose of the prediction equations is to relate measurable physical parameters describing the aircraft to observed measures of R&M. The accuracy of the method depends very much on the consistency of the data. In addition, there are other factors affecting R&M that will not be accounted for in the equations, but which could cause errors. Such error sources include the data collection procedure, definition and capture of variables and data, aircraft reliability growth, inconsistent maintenance policies, differing operating and environmental conditions, small sample size, and the use of few parameters to reflect complex design effects. It has been assumed that the influence of these factors is relatively small.

Derivation of prediction equations - Equations for all twelve aircraft systems were derived using multiple regression analysis of the defect rate and mean time to repair data with various parameters, alone and in combination with others. Over 90 parameters were tested, of which 28 and 19 were finally selected for the reliability and maintainability equations respectively. Several possible forms of equation were investigated in each case, some incorporating the influence of time on reliability (called time improvement factor, TIF) resulting from different technology standards and design practices. Prediction equations were only accepted if there was sound engineering basis for the inclusion of the parameters, and the trends produced were logical. Points that did not fit an otherwise clearly defined trend, either as a result of known exceptional features or as a result of a known error source (known as outliers), were discarded. For example, Lightning landing gear data was discounted, as the aircraft was notorious for its poorly sized tyres, which were very narrow in order to stow within the thin wings of the type.

Total aircraft defect rates - The total aircraft defect rate is found by adding the system defect rates. The accuracy of the total defect rate prediction is well illustrated by using the reliability equations to compare the predicted and recorded reliability of a number of aircraft. The results of the comparison, together with a best-fit line and 'goodness of fit' metrics are shown in Figure 15.

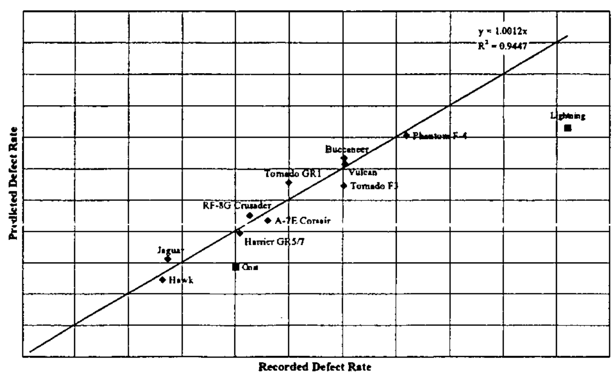


Figure 15. Predicted vs. Recorded Defect Rates.

Only the results for Lightning and Gnat are poor predictions; these were both significant outliers in some of the derivations and were excluded from the derived equations. The policy of excluding outliers tends to increase the total error of the excluded aircraft, but the resulting equations better represent engineering trends, and thus should have superior predictive ability. Plotting of actual and predicted rates for each aircraft by system (see Figure 16 for the Harrier GR5/7 as an example) indicate that the accuracy of the prediction is a consequence of good system level prediction, rather than fortuitous cancellation of system errors.

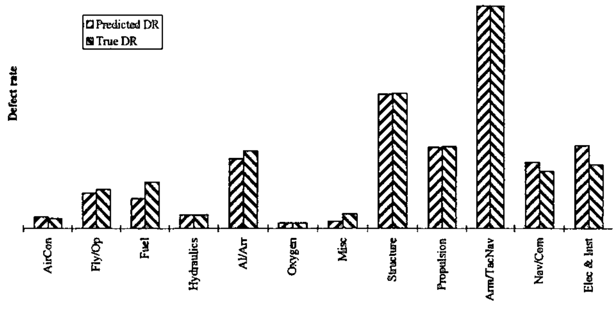


Figure 16. Predicted and Recorded Defect Rates, By System.

Maintainability prediction equations - As noted above, the maintainability equations were derived using data for the ten aircraft in the database operated by the RAF. Maintainability equations for the MTTR of each of the twelve aircraft systems were derived using the same multivariate regression process as used for the reliability predictions. Time improvement factors are not used in the maintainability prediction equations, since maintainability is not dependent on component design to the same extent as reliability. However, factors are employed to account for 'design for maintainability', and the resulting improvement in the accessibility of systems.

The total aircraft mean time to repair is defined as the total of the defect man-hour rate divided by the total defect rate. The results from the R&M prediction equations may be combined to generate an overall defect man-hour rate (man-hours per flying hour). Figure 17 shows a comparison of predicted and recorded defect man-hour rates for various aircraft.

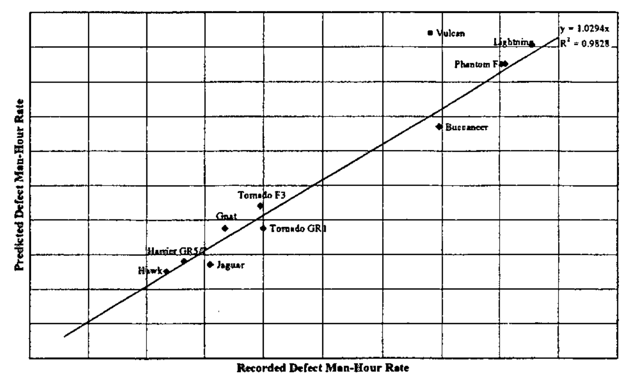


Figure 17. Predicted vs. Recorded Defect Man-Hour Rates.

LSV-F PREDICTIONS - The R&M forecasts for the LSV-F were produced using the prediction equations, and drawing upon 47 available inputs. The inputs ranged from the date of the first flight of the aircraft type, through empty weight, to whether the aircraft carried a primary radar. It should be noted that the outputs from some of the prediction equations were modified to account for special features of the LSV-F, such as additional effort expected in the detailed design stage to reduce support requirements. If no adjustments to the predictions are allowed, the DMHR is increased by 9%.

It would be misleading to compare the predicted defect man-hour rate and its components, the defect rate and the mean time to repair a defect, for the LSV-F with published data available for other aircraft. The LSV-F predictions are based on the maintenance policies and data collection standards of the RAF. Other aircraft operators use figures derived from a different base; some include planned as well as corrective maintenance, or consider on-aircraft maintenance time only. The study compared the predicted rates for the LSV-F with the predicted rate of other combat aircraft. Figure 18 shows the results of the comparison, scaled relative to the predicted values of Tornado GR1.

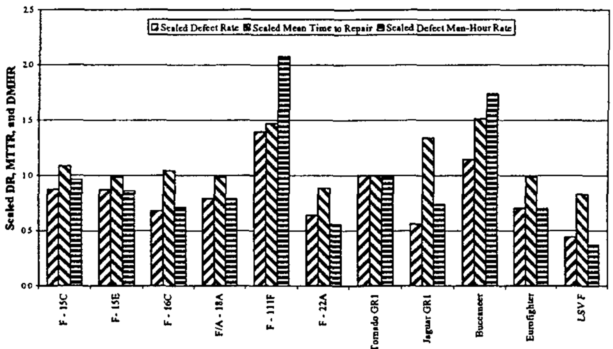


Figure 18. Predicted R&M Quantities.

The comparison shows that the defect-related maintenance requirement (the DMHR) of the LSV-F is considerably lower than that of all the other aircraft, being nearly half of that predicted for Eurofighter and nearly a third of that predicted for Tornado GR1. The maintainability prediction for the LSV-F structure penalises the use of composites and the relatively poor accessibility due to the low aspect ratio all-wing configuration. Except for the structure system, the maintenance requirement of every system of the LSV-F is less than that of each of the other aircraft. The relative advantage of the LSV-F over the other aircraft is less pronounced in maintainability (the MTTR) than in reliability (the DR). It is likely that some maintainability advantages of the LSV-F are not reflected in the maintainability prediction equations.

Influence of technology - The LSV-F (and F-22 and Eurofighter) predictions benefit from the increased reliability of modern systems reflected in the Time Improvement Factors in the reliability prediction equations. By eliminating this factor it is possible to judge whether the LSV-F and its 'contemporaries' are the most supportable simply because they use newer technology, or whether the designs are fundamentally superior. Setting the technology datum to 2002, the assumed first possible flight date of the LSV, results in an overall flattening of the distribution of the results, although the pattern is very similar. The LSV-F remains best by a considerable margin, but its nearest competitor becomes the Jaguar, a far less capable aircraft. F-22 slips to fourth in the ranking, being overtaken by the less capable F-16. The implication of this is that the supportability advantage of the LSV-F derives partly from the application of new technology, but mainly from the fundamentals of the design.

Future Developments - As the LSV-F was single point design for a given mission specification, it is unlikely that the actual design will progress further than at present. However, the design philosophy and many of the models will be taken forward and updated for use with other DERA aircraft design and analysis tools. Of particular interest are the mass and aerodynamic estimation methods for the flying wing configuration. The R&M prediction equations will form the basis of an updated model, which will be compatible with the LCC model described in Part I. This will contribute to a powerful and flexible suite of aircraft design and analysis tools, capable of designing and optimising for either minimum mass, LCC, support effort, or eventually, availability-cost.

CONCLUSIONS

This paper has described the methods and results from two DERA-sponsored University research programmes. The first, performed by the College of Aeronautics, Cranfield University, developed a computerised design and optimisation tool to minimise the Life Cycle Cost of combat aircraft. The tool and the results from some studies were presented in Part I of this paper. The second research programme, performed by the Department of Aeronautics, Imperial College, produced a similar tool to investigate the supportability gains that could be achieved by an aircraft designed for maximum supportability. The resulting aircraft, the Low Support Vehicle, and the methods used to assess its supportability were described in Part II of this paper.

Both research programmes have shown that design for reduced cost is possible, but that quantifying the benefits is difficult and requires extensive modelling effort. The LCC model has shown that reduced through-life cost will not always be achieved by reducing support costs. Although O&S contributes approximately 50% of the through-life cost, the economic impact of increasing reliability and compromises to the design may outweigh, in life cycle terms, the benefits of reduced O&S costs. This matter is further complicated by the difference between discounted and non-discounted costs.

The design characteristics resulting from the cost and support design drivers are considered to improve future aircraft supportability, and therefore improve future combat aircraft peace time and war time availability, whilst reducing through-life costs. This in turn should lead to aircraft capable of delivering a set level of performance for reduced cost, maximising 'value' in the military sense, and leading to a situation that will be beneficial for both customer and manufacturer alike.

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